A Strategic Vision for Fermilab Participation in CMS Upgrades

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Version 1.1

1. Introduction

The CMS Collaboration is undertaking an extensive planning process to prepare for CMS upgrade activities that extend well into the next decade. The Fermilab CMS group is currently involved in several of these activities, and is evaluating the availability of Fermilab resources for existing commitments and possible future commitments for an expanded role in CMS upgrade projects. The upgrades will require substantial funding from funding agencies, and laboratory expertise is expected to be invaluable to many of the upgrade tasks. Any strategy that is developed for Fermilab participation in the upgrades must be driven by CMS physics goals, be able to accommodate changes in projected performance of the LHC, and be flexible enough to accommodate changes in schedules and funding profiles. The purpose of this document is to define a strategic vision for the Fermilab CMS group, summarize current activities, identify core upgrade activities that are a Fermilab responsibility and have high priority for CMS, and identify opportunities for future involvement that apply the strengths and unique capabilities available at the laboratory.

2. Strategic Vision and Goals

FNAL is the national host laboratory for USCMS and as such should partner with the US universities bringing our special technical expertise to bear on the most critical issues (FPIX is a good example). As the largest USCMS institution (in fact we're second only to CERN on CMS) we can and should take on a range of challenging issues which are the highest priority for CMS and USCMS. Fermilab should work towards establishing a leadership role in CMS upgrades as the laboratory did in the past for CMS construction. Moreover, participation in the upgrades should take advantage of the unique capabilities available at the laboratory, and should be tailored to CMS and USCMS physics goals. In order to fulfill this vision the Fermilab CMS group should work towards achieving the following goals, which are described in greater detail at the end of this document:

1. Identify opportunities for work on CMS upgrades that are well matched to laboratory expertise and available resources, and establish Fermilab commitments within CMS.
2. Identify core upgrade activities and continuing responsibilities, and ensure that these activities and responsibilities have the necessary resources to be successful.
3. Work towards establishing leadership positions in CMS upgrade activities for Fermilab staff.
4. Develop partnerships with CMS collaborating institutions and the LPC in order to establish Fermilab as an important center for CMS upgrade activities.
5. Identify upgrade projects that are beneficial to maintaining or improving capabilities at Fermilab.
6. Ensure that postdocs are engaged in upgrade activities and that they are aligned with Fermilab objectives.

The strategy for the Fermilab CMS group must be flexible in order to accommodate changes in the physics goals, schedule, and funding profile of the upgrade program. Figure 1 summarizes the current timeline for LHC shutdowns, which determine the schedule for CMS upgrades. The shutdowns are referred to as Long Shutdown 1 (LS1), followed by long shutdowns LS2 and LS3. Needless to say, the dates and durations of the shutdowns are subject to change, and plans will likely change with time. For now, the plan is that after LS1 the LHC is expected to achieve the intended design energy and luminosity. The luminosity is expected to increase steadily prior to the LHC Phase 1 upgrade, and continue increasing after the upgrade. Radiation damage to parts of the detector will require the replacement of specific subsystems. New electronics will be required to handle increasing data rates, and new detector configurations will be required to avoid significant degradation of detector measurements in the presence of high pileup. The Phase 2 LHC upgrade, which is referred to as the High Luminosity LHC (HL-LHC) will produce even higher luminosities after LS3, requiring additional upgrades.

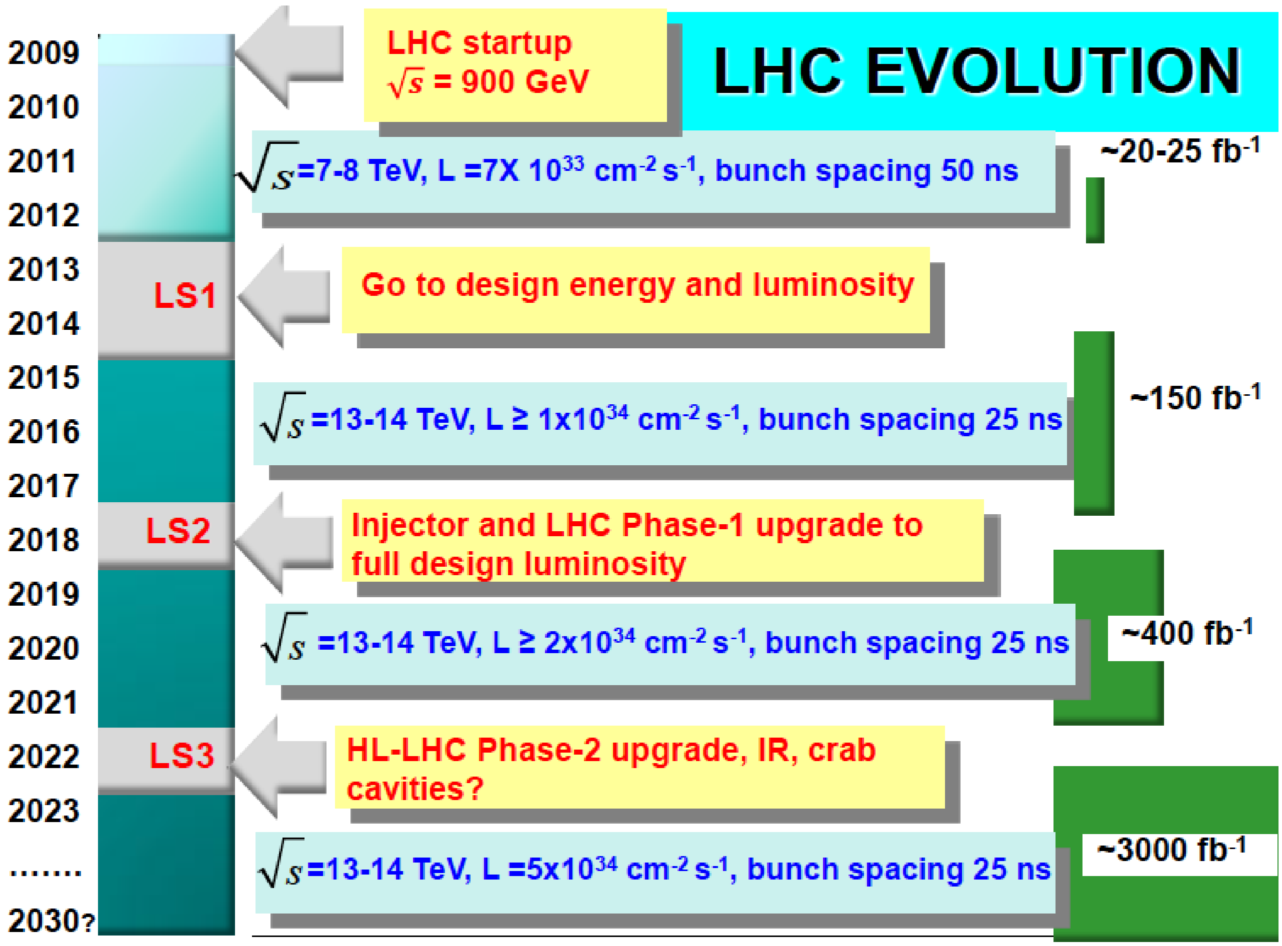

Figure 1: *Timeline for LHC shutdowns and upgrades.*

The first three goals listed above are near term goals. The goals emphasize the importance of working on upgrade activities that are well matched to Fermilab capabilities, and contributing to upgrades that have high priority within CMS to maximize the physics potential of the experiment.

The fourth and fifth goals are more future oriented. The first of these deserves special attention, in that the Fermilab CMS group is in a unique position to identify new opportunities by further developing partnerships with the LPC and universities. The LPC attracts CMS members through the CMS Fellowship program, the dynamic environment of lectures and workshops, and the computing resources that make it easy to access CMS data for physics analyses. In order to ensure the future vitality of the Energy Frontier at the laboratory, the Fermilab group should partner with the LPC to facilitate its growth into an important center for upgrade activities. The fifth goal is specific to Fermilab's future with an emphasis on developing new laboratory capabilities, engaging the laboratory staff, and utilizing and strengthening facilities.

The sixth goal is significant in that the work of Fermilab postdocs must be aligned with laboratory objectives, which will enable them to develop the appropriate balance of skills to successfully compete for jobs in an increasingly challenging environment. The balance should include experimental techniques, physics analysis, presentation skills, and management experience.

3. The CMS Detector and Fermilab Contributions

3.1 Tracker

The Fermilab CMS group has played a leading role in the CMS tracker project since the original design of the experiment, and is well positioned to continue in this leadership role for tracker upgrades. Fermilab was responsible for assembling and testing half of the TOB (Tracker Outer barrel) modules and Fermilab engineers and technicians played a large role in fixing/repairing the CMS flurocarbon cooling plant. Fermilab was responsible for the forward pixel detector (FPIX) during the CMS construction project. FPIX was assembled, tested and commissioned at Fermilab's Silicon Detector (SiDet) facility before being shipped to CERN. Fermilab was responsible for the design, procurement, quality assurance, and assembly of the mechanical support and cooling lines. This included the support structure for the half disks, the half cylinders, the blade structure and cooling channels, and the end flange. Fermilab designed, procured, performed quality assurance, and installed all of the electronic circuits required for FPIX. This included different types of flex circuits, port cards, adapter boards, power filtering boards, and all test cards and test-stands for testing the individual components such as the pixel readout chips (ROC), Token Bit Manager (TBM), all of the required ASICs, pixel modules, pixel panels and system integration tests.

A large number of Fermilab scientists, engineers, and technicians were involved in the construction of the FPIX detector, as indicated here in alphabetical order:

- Scientists: Atac, Butler, Hahn, Joshi, Kwan, Tan, Uplegger, Yun
- Engineers: Baldin, Derylo, Fang, Gingu, Howell, Krider, Lei, Los, Matulik, Prosser, Roman, Turqueti
- Technicians: Butler, Gillespie, Gonzalez, Hawkes, Jakubowski, Montes, Sellberg, and other techs in the PPD/EED Department.

Fermilab was responsible for setting up the lab at the CERN Meyrin site (Kwan, Tan, Uplegger). After the detector arrived at CERN , the pixel half disks were reinstalled on half cylinders by a team from Fermilab (Hahn, Kwan, Butler, Wilson), and installation tests and installation were done with help from the Fermilab group (Kwan, Howell, Derylo, Butler). During commissioning, Uplegger was based at CERN for approximately one year to help commission the detector.

3.1.1 Tracker Improvements During LS1

During LS1, the entire pixel detector will be extracted to enable the insertion of a new beam pipe. Extraction is expected to happen soon after data taking has been completed. CMS will then have about 10-11 months to service the detector. All broken and bad channels will be fixed or replaced, and all cooling lines within half cylinders will be replaced. After completing the repair, the pixel detector will be tested and calibrated. Re-installation is expected to occur around May 2014.

To prepare for the installation of the Pixel Phase 1 Upgrade, CMS plans to perform an insertion test after the new beam pipe and beam pipe support have been installed. This includes the construction of a mock-up of a half cylinder for the insertion test.

Another project requiring substantial effort during LS1 is the construction, assembly, testing, and installation of a pilot pixel system into one or two of the existing FPIX half cylinders. The Pixel Phase 1 Upgrade requires a new readout chip (ROC) that entails a fully digital chip running at 400 MHz. CMS will use DC-DC conversion for this subsystem. The motivation for the pilot system is to build a small pixel detector using the new ROC and readout electronics, and install it as the third disk in the current FPIX detector. The Fermilab engineering teams (including both electrical and mechanical engineers) are responsible for the design, procurement, and testing of all parts needed for the pilot system. Installation into the half cylinder will be done by the Fermilab team at CERN.

3.1.2 Pixel Phase 1 Upgrade

Since late 2008, the Fermilab team has been working on the Pixel Phase 1 Upgrade, specifically the FPIX detector. Fermilab is responsible for the design of the entire FPIX system for the upgrade. The goals are to have a new lightweight detector that is better suited to handle high luminosity.

The R&D work for the upgrade can be broadly classified into two main areas: mechanical (including cooling) and electrical. For mechanical work, Fermilab is responsible for defining the geometrical configuration, designing the mechanical support and the cooling lines, building the new lightweight half cylinder, prototyping, testing, and performing finite element analysis (FEA) studies. People involved in this work are: Kwan, Lei, Howell, Derylo, Gonzalez, Butler, Eileen Hahn, John Rauch and the Design group.

The team has a well-developed design that satisfies the goals of the upgraded pixel detector, and is currently building a sector (1/4) of a complete half disk and will use this to study thermal performance characteristics. The team will also build a mock-up of the entire half cylinder in order to investigate issues related to available space installation and detector assembly.

For cooling, CMS decided to replace the fluorocarbon (single phase) cooling system with a CO_2 (bi-phase) cooling system. Fermilab has constructed a prototype CO_2 cooling plant at SiDet so that tests to demonstrate CO_2 cooling can be performed, and the design and its thermal performance can be validated. People who are involved in this effort are Kwan, Schmitt, Voirin, Tope, Lei, and Howell. The plan is to build the cooling system for a complete half cylinder and then study performance characteristics such as pressure drop and flow rate.

For electronics, the Fermilab team is responsible for designing the new digital opto-hybrid readout, which transmits data from the detector to the data acquisition system. The team accepted this responsibility for the entire CMS pixel detector (including the barrel pixel system). The prototype system works well, but new ASICs are needed to complete testing.

For FPIX electronics, Fermilab is responsible for designing all electronic circuits. This includes a High Density Interconnect (HDI) flex circuit, a lightweight aluminum cable, and a port card. The prototypes of these components will be used in the pilot system. People who are involved in this effort are Kwan, Los, Matulik, Prosser, Chramowicz, and Andresen.

For DC-DC conversion, the Fermilab team is responsible for testing the prototype and its effect on the forward pixel system. The team will use the prototype DC-DC conversion ASIC to power up part of the pilot system.

Other electronics activities include the testing of new 2x8 pixel modules. Fermilab purchased a new automatic probe station that will be used to perform the wafer testing.

Looking beyond the Pixel Phase 1 Upgrade, Fermilab is involved in developing a new pixel detector for HL-LHC. If necessary, this new pixel system could be used to replace the inner barrel layer before the LS3 shutdown. The effort is concentrated in two areas: radiation hard sensor development and a new pixel readout chip. The rad-hard sensor development is a large collaboration with participants from Colorado, Purdue, SUNY, UMiss, Milan, Torino, and Tennessee. The collaboration is testing prototypes of candidate sensor technologies, such as 3D silicon, diamond, thin planar silicon, and MCZ silicon. People at Fermilab who are involved in this effort are Kwan, Uplegger, Rivera, Prosser, Tan, Yang, Tran, and Ito. The new pixel readout chip is a collaboration that involves Fermilab, INFN, TAMU, Strasbourg, and possibly CERN. People at Fermilab who are involved in this effort are Christian, Kwan, and Deptuch.

3.1.3 Phase II Tracker and Track Trigger

At the very high luminosities expected for HL-LHC, the CMS detector will need an upgraded trigger to survive very high pileup. Although Fermilab has not participated in the current implementation of the CMS Level 1 (L1) trigger, expertise at the laboratory in track triggering and capabilities in ASIC engineering give the Fermilab CMS group an advantage when competing for work on the design and implementation of a Level 1 track trigger.

In order to increase the trigger efficiency and decrease the L1 trigger accept rate when confronted with high pileup, CMS is investigating ways in which a track trigger can be incorporated at Level 1. Fermilab is currently involved in an R&D effort with the goal of developing technologies that will enable an all-silicon track-based trigger at L1 for HL-LHC. An L1 track trigger must be a factor of 400 faster than a Level 2 SVT/FTK-like system, as it is currently used in CDF/ATLAS. This is accomplished by using hit correlations between pairs of silicon sensors that are separated by approximately 1mm to eliminate hits from low transverse momentum tracks. Members of the Fermilab group are investigating technologies related to the implementation of such a system, including:

- 3D integration of sensor and readout using through-silicon-via wafers and oxide bonding technology.
- Interposers that can connect top and bottom sensors.
- Development of high yield large area pixilated arrays by combining 3D readout/sensor integration and active edge technology.
- Development of very high speed asynchronous data transmission ASIC technology, which can send large volumes of data without using a system clock.
- Development of off-detector algorithms and track finding systems.
- Development of large area modules and mechanical support.

During the past three years, Fermilab has been involved in R&D focused on developing a CMS track trigger. The R&D includes the development of a 3D CMS track trigger chip, called VICTR (a first for HEP); designs for mechanical supports; techniques for module construction and bump bonding; a design for an “asynchronous pipeline” chip that will demonstrate the functionality for fast pipelined track-stub readout; prototype support rods; and initial fabrication of “active tile” prototypes aimed at combining 3D electronics and active edge sensors to enable affordable large area pixelated arrays.

Over the next three years, the plan is to develop technologies that enable the construction of prototype 10x10 cm track-trigger doublet modules, and investigate the industrialization of trigger modules. The plan is to:

- Demonstrate the fabrication of fully active tiles which can be butted on all four sides, using 3D through-silicon-via electronics to provide back-side connections in the body of the device and active edge processing to minimize edges.
- Develop a design and provide prototypes for on- and off-detector electronics to provide a set of tracks for every LHC beam crossing (including 25 ns operations).
- Fabricate and test prototype readout ASICS that will find clusters and track stubs with transverse momentum greater than two GeV.
- Build prototype modules with fully functional tiled arrays and readout ASICs.
- Work with industry and groups at SLAC and UCSC to develop technologies to integrate 8” CMOS readout and 8” sensor wafers into active tiles.

The effort at Fermilab is led by Lipton. Additional Fermilab people working on the project are W. Cooper and Spiegel. Z. Ye, a Fermilab RA, worked on testing the first VICTR chip, however he is leaving to join the faculty at UIC. Chetluru, a Fermilab RA, will be testing the next chip. The testing is performed at SiDet, and sample technologies will be tested in Fermilab’s test beam facility.

Upgrade Task	Shutdown	Motivation
Pilot pixel detector	LS1	Third disk on current FPIX. Gain operational experience with new ROCs/TBM/FED and power system.
New pixel detector	LS2	New design and readout.
L1 Track Trigger	LS3	Provides L1 triggering on tracks in the high pileup environment of HL-LHC.
New pixel detector	LS3	Requires new sensor technology for HL-LHC. Currently exploring 3D Si sensor, diamond (RD42), thin planar Si sensors.
New strip detector	LS3	Currently evaluating radiation hardness and geometries.

Table 1: *Summary of Tracker and L1 Track Trigger upgrade activities.*

3.2 Calorimetry

Fermilab has had a leadership role in the CMS Hadron Calorimeter (HCAL) since its design and construction and participated in the building, commissioning and maintenance of the calorimeter. It is natural for Fermilab to leverage the local expertise and participate in HCAL upgrades. Table 2 summarizes HCAL improvements and upgrades that the Fermilab CMS group is currently involved in.

Anomalous signals occurring in the Hadronic Forward Calorimeter (HF) PMTs were first observed when HCAL modules were exposed to test beams and later observed during collision data. The anomalous signals in HF occur from particles interacting around the PMT and produce a signal that arrives earlier than the signal from Cherenkov light produced by particles in the absorber of HF. In order to avoid early triggering it was necessary to apply a veto to the empty bunch crossing before the collision crossing. This will not be possible when the LHC operates with a bunch spacing of 25ns. The replacement of the HF PMTs during LS1 with thin window multi-anode PMTs will reduce the effects from beam related anomalous signals, and will enable the use of HF in the trigger in the future. Furthermore, having multiple readouts for the same cell will provide an additional method for rejecting anomalous signals. The HF PMT upgrade will reduce the contribution of anomalous signals and allow HF to be included in the trigger if the LHC operates with 25ns spacing. Part of HF has been instrumented with replacement PMTs in order to test their performance in the working environment and has been demonstrated to have less anomalous signals. Chlebana is leading the group to develop filters for anomalous signals. Tkaczyk is the HCAL integration group co-convenor who is responsible for the planning of the HCAL upgrade work during LS1. Fermilab has been involved in project planning, setting specifications of the PMTs and analog cables, and designing and fabricating the PMT sockets/baseboards. Whitmore, who is the HCAL Detector Systems Co-convener, also has been leading the slow controls upgrade and CCM refurbishment projects that will be installed in LS1.

The Hybrid Photo Diodes (HPDs) used to readout the Hadronic Barrel (HB) and Hadronic Endcap (HE) sections also have anomalous signals occurring from ion feedback, HPD discharge, and coherent noise from several HPDs within a readout box. Software filters were developed for HF and HBHE which separate anomalous signals from collision signals by looking at the pulse shape and isolation. The filters become less efficient for high pileup and a shorter bunch spacing (25ns vs 50ns) where the signals from adjacent crossings can distort the pulse shape. The HPDs in HBHE will be replaced with silicon photomultipliers (SiPMs) during LS2. At that time the number of depths being readout in HBHE will be increased in order to improve the performance in the expected high pilup environment. The multiple layers will enable better separation between the pileup occurring in the inner layers and the hard collision energy deposits in the outer layers. The depth segmentation in HE will also enable a better determination for radiation damage that depends on depth, by determining calibration constants for different depths as a function of time. Cheung has coordinated the simulation upgrade effort, which will be essential for the physics justification of the HCAL upgrade. Freeman and Anderson have led the efforts on SiPM device studies, control card engineering and simulations. Whitmore is working with engineers to develop and test the ADC/TDC QIE chip for the upgrades. Joshi is responsible for the design and implementation of the hardware database for the HCAL upgrade.

HPDs are also used to read out the Hadronic Outer Calorimter (HO) which is located outside the solenoid. The HO acts as a tail catcher and can be used to improve the measurement of very high energy jets. The HPDs were found to have a high discharge rate when positioned in the lower magnetic field found outside the solenoid. In order to preserve the HPDs it was necessary to turn off HO rings 1 and 2. The HO HPDs will be replaced with SiPMs during LS1. Part of HO has been instrumented with replacement HPDs in order to gain operational experience. The SiPMs have much better signal to noise ratio than the existing HPDs and can also be used to measure muons. Recently HO was included in the PFlow Jet reconstruction and seen to improve the jet measurement. Freeman is leading the HO SiPM replacement effort, and Anderson performed studies to understand and specify the characteristics needed by the SiPM and developed the code to simulate the SiPM in CMSSW.

Upgrade Task	Shutdown	Motivation
HF PMTs	LS1	Reduce beam related anomalous signals
HO SiPMs	LS1	Improved signal to noise separation, allows inclusion of HO rings 1 and 2
HCAL Splitters	LS1	Phase in trigger upgrade
HCAL Construction Database	LS1	Track parts
Upgrade Simulation	LS1	Needed for physics justification for the HBHE upgrades
MicroTCA Test Stand	LS1	Used for testing
QIE10	LS1.5 (ETS ~2016)	HF + HBHE FE electronics
HF FE Electronics	LS1.5 (ETS ~2016)	Support new devices and increased bandwidth
HBHE FE Electronics	LS2	
HBHE SiPMs	LS2	Replace HPD, and provide increased depth segmentation
Forward Detector Concept Working Group	LS3	Design of an integrated forward detector for HL-LHC

Table 2: *Summary of HCAL upgrade activities.*

The HPD replacement in HBHE with SiPMs increases the number of depths and will require updating the simulation and reconstruction code. A Monte Carlo simulation including the simulation of the new SiPMs and allowing different options for the depth readout has been developed. Reconstruction of objects using the calorimeter, such as jets and missing transverse energy, will need to be updated to take advantage of the additional information. The Global Event Description (GED) makes use of all relevant detector information when reconstructing physics objects in order to maximize the resolution. Although the Fermilab CMS group is not directly involved in the development of the GED, the reconstructed objects are needed for studies demonstrating the performance with increased depth segmentation. This is an area where the synergy between the Fermilab group and the LPC can be leveraged. The LPC provides a focus for CMS activities, and the CMS Fellowship program attracts leaders who can build up groups working on upgrade activities. With this in mind, Fermilab should explore strategic partnerships with the LPC that are mutually beneficial. This is discussed in more detail in the section “Strategic Partners”.

HCAL signal splitters will be installed in LS1 allowing the signal from the front end to be split so that signals are sent to both the current L1 VME trigger and the new L1 MicroTCA trigger. This enables commissioning of the L1 trigger in parallel with data taking.

3.3 Muon Detectors

Fermilab was one of the original construction sites for the Cathode Strip Chambers (CSC) that are currently installed in the CMS detector. Fermilab machined the panels for the CSC chambers and built 50 complete chambers.

During LS1, CMS is planning to install two additional endcap muon chamber stations that were left uninstrumented during the construction phase because of budgetary restrictions. A total of 72 chambers are required to equip both endcaps of the ME4/2 stations. For these additional chambers, Fermilab is responsible for procuring, cutting, drilling and strip milling the panels. Completed panels are shipped to CERN, where a new muon production factory has been built with assistance from Fermilab technical and engineering staff. A total of 504 panels are needed for the construction effort. The level of effort for producing these panels at Fermilab is 1 engineer and 3 technicians. Although Fermilab previously built and tested complete chambers, the cost of Fermilab labor and overhead was considered too high compared to setting up the factory at CERN.

During LS1, the readout and control electronics for the inner muon chambers (ME1/1) will be replaced in order to increase the granularity of the readout. The new electronics are being designed and built by a consortium of US Universities.

Upgrade Task	Shutdown	Motivation
ME4/2 stations	LS1	Increase efficiency at L1 trigger and offline for reconstructing high eta muons. Reduce L1 trigger rate for muon objects.
ME1/1 electronics	LS1	Increase readout granularity for inner muon chambers, improving efficiency at higher pileup.

Table 3: *Summary of Muon upgrade activities.*

3.4 Central Data Acquisition System

Fermilab has been a partner in the CMS DAQ since the R&D phase, partnering with MIT, UCSD and UCLA. The DAQ is a collaboration of US groups and CERN, with the US groups making up approximately one third of the total effort. Fermilab supports the effort with 1 - 2 FTEs and also manages the overall USCMS contribution. The specific responsibilities of Fermilab are the event builder and storage manager software and DAQ operations support.

The heart of the DAQ is formed by a two stage event builder: the first stage does an initial combination of data inputs and the second stage builds entire events. During LS1, CMS plans to rebuild the first stage of the event builder and upgrade the network technology in both stages to 10GbE. Fermilab plans to support this effort and continued software maintenance and development of the event builder and storage manager software packages at the level of 1 FTE computing professional, based at CERN.

Upgrade Task	Shutdown	Motivation
New FEDBuilder	LS1	Replace expensive and obsolete technology (Myrinet). Increase event builder 1st stage throughput and accommodate higher occupancy subdetector front ends.
Upgrade EVB network	LS1	Replace obsolete technology (GbE). Increase throughput of 2nd stage of event builder.

Table 4: S*ummary of DAQ upgrade activities.*

3.5 High Precision Forward Spectrometer

The High Precision Forward Spectrometer (HPS) is a new proposal for CMS that is a relatively low cost improvement to the physics capability and not expected to require significant Fermilab resources. Currently one Fermilab Scientist is involved. This project provides an opportunity for people to get involved in many stages of detector proposal and development. The HPS is a set of very forward (+/- 240 m from the CMS collision point) proton detectors with precision tracking and timing. Fermilab is working together with US and European Universities, and some physicists from Lawrence Livermore National Laboratory, on a proposal to install the HPS in 2014. This new CMS subdetector would enable the measurement of p + X + p reactions, where X can be a Higgs boson, a W+W- pair, or other simple states. However this must be done at high luminosity, with perhaps 20 - 40 interactions in the bunch crossings, and the protons are often from different pp collisions. High precision timing (order 10 ps) of the protons can suppress this background, by determining the collision point to about 2 mm along the beam direction.

At Fermilab, Albrow (CMS) with Ronzhin and Ramberg have developed novel detector designs, based on quartz Cherenkov radiators and SiPM photodetectors, to solve this problem. Prototypes, which must be edgeless and radiation hard, have been made and tested in test beams. So far a resolution 16 picoseconds has been demonstrated in a 2D hodoscope with 3x3 mm^2 elements, and with multiple measurements per proton ("timetrack"). This detector has other applications, e.g. in beam diagnostics.

A Technical Proposal is in preparation and the HPS has not yet been reviewed/approved by CMS. Stage 1 for 2014 involves installation of a moving beam pipe section, silicon tracking and fast timing detectors. Stage 1 has acceptance mostly for high masses M(X) > 200 GeV; Stage 2 would follow later at 420 m and with sensitivity to a low mass Higgs (e.g. M(H) =125 GeV).

3.6 Forward Detector Upgrade for HL-LHC

After LS3, the foreseen luminosity delivered by the LHC will be in excess of 5×10^{34} $cm^{-2}s^{-1}$ and the total integrated luminosity goal for the run period after LS3 is in excess of 3000 fb^{-1}. A forward detector working group, co-led by a USCMS senior scientist, has been established by CMS to explore upgrades in the forward region that can cope with high luminosities. Current physics benchmarks for the forward detector are Vector Boson Fusion processes at high mass, Multi-TeV SUSY and very heavy Z'. The CMS GED algorithm is ideal for ensuring both good jet resolution and e/gamma separation in the very forward region, however this may require tracking information in the forward region. A calorimeter upgrade task force was appointed by the Forward Detector working group, and is comprised of mostly USCMS institutions. Radiation hard calorimetry options are being explored in this task force, as well as upgrade simulations. It would be natural for Fermilab to take a leading role in this area, however to date the contributions by Fermilab have been modest.

3.7 Simulation For Upgrades

Justifications for the upgrades require realistic simulations of the new detector configurations and complete physics analysis to demonstrate any performance improvements or degradation due to radiation damage. Harry Cheung is the co-leader of the Tracker simulation group which provided the simulation used for the Phase I upgrade TDRs. In order to get the full benefit of new detector geometries and functionality it is necessary to update the fundamental object reconstruction.

3.8 Software Framework and Offline Reconstruction

The Fermilab CMS group was the initiator of the major re-engineering of the CMS software system that started in 2005 and resulted in the successful delivery of the CMSSW framework. Fermilab led this effort and staffed the core team that designed and developed the framework components and many CMSSW applications. Yagil acted as the first CMS software (L1) coordinator for this effort in 2005-2006. Sexton-Kennedy followed as L1 deputy offline coordinator in 2010-2011, and L1 offline coordinator in 2012-present. Members of the Fermilab group also served in offline L2 management positions in the areas of Simulation (Stavrianakou in 2005-2006, Elvira in 2006-2007, and Banerjee in 2010-2011), Framework (Sexton-Kennedy in 2005-2010, Jones in 2010-present), Data Quality Monitoring (Maeshima in 2010-present), and Analysis Tools (Rappoccio in 2011-2012).

Fermilab was in a unique position to drive the CMSSW re-engineering effort based on experience in the Scientific Computing Division (SCD) that was accumulated during the Tevatron years (SCD was referred to as the Computing Division during that time). The Fermilab SCD CMS Department, and the SCD Accelerator and Detector Simulation Support (ADSS) department are an invaluable resource with expertise in the areas of software design, implementation, and optimization, as well as tools such event generators (Pythia), detector simulation kits (Geant4), and analysis frameworks (ROOT). These resources, and the experience acquired by the offline team during the commissioning and first running period of the CMS experiment, put Fermilab in a strong position to accept major responsibilities in the program to address the challenging software tasks that await the CMS upgraded experiment in 2014 and beyond.

The CMS offline program also includes the development of the software algorithms to reconstruct physics objects such as jets, electrons, photons, and muons. Fermilab physicists are very experienced in the areas of jet reconstruction and tracking, in particular. Burkett led the CMS tracking group in 2008-2010, Elvira and Harris led the JetMET group in 2008-2009 and 2010-2011 respectively, and Cavanaugh led the particle flow group (now called the Global Event Description, GED) in 2007-2008. The Fermilab group made core contributions to algorithm development and object commissioning first with simulated events, and later with collider data. The GED algorithm is a comprehensive approach to object reconstruction based on the identification and reconstruction of individual particles by type before being clustered into objects such as jets or missing transverse energy. The GED demonstrated the best performance compared to other methodologies and became the default CMS algorithm to reconstruct physics objects. The high luminosity environment expected from the upgraded LHC poses a challenge to the performance of the GED algorithm, which is highly tuned to the present detector. The re-engineering and tuning of the GED algorithm is necessary to adapt to the new readout geometry and detector features, while maintaining and eventually improving the current performance in high pileup events. This task is a challenge and constitutes an opportunity for the Fermilab group to get involved in this effort. The GED is also a key element in the simulation software to be used in the physics studies to make the case for the different elements of the CMS upgraded detector. Fermilab is uniquely positioned to play a significant role in making the case for the upgrade given that its staff not only possess expertise in the areas of detector simulation, physics, and reconstruction algorithms, but also leads the simulation upgrade effort (Cheung).

Looking towards the future, the LHC's increasing luminosity and the resulting need for more computing resources will create challenges for CMS software developers. The new generation of computer architectures with their large numbers of computing cores are not well matched to the design of CMS software. The solutions to this challenge require an increase in parallelism, such as increasing the number of sockets in a system, number of cores in a socket, hardware threading, instruction level parallelism, pipelining, and vector instructions. In order to make the software as thread safe and vector friendly as possible, a significant amount of rewriting code will be required for the framework and applications. A new programming paradigm will be needed, which implies new coding techniques and therefore a significant amount of training and user support. This path is, however, unavoidable given the constraints imposed by the evolution of computer hardware and presents Fermilab with a unique opportunity to make a difference in CMS while training young physicists in technologies that are very attractive to prospective employers. Within CMS, only the CERN SFT and the Fermilab SCD-CMS and SCD-ADSS departments have the interdisciplinary teams of physicists and computing engineers with the level of expertise and experience to undertake these projects. The Fermilab SCD-ADSS department is involved with collaborators at CERN in exploratory R&D to transform the Geant4 toolkit for High Performance Computing.

Changes in LHC conditions and detector improvements that are expected after LS1 and LS2 require new versions of CMSSW to first demonstrate the need for an upgraded detector, commission the detector, and finally reconstruct collider data. The current SLHC software within CMSSW bears little resemblance to the standard release in the critical area of tracking, and needs work in many areas to absorb back-ports of important improvements. The Hadronic Calorimeter (HCAL) will be significantly upgraded, including new Barrel and Endcap photodetectors that will change the electronic output signal in a significant way. Software at the detector simulation (geometry, simulated hits, digitized hits, reconstructed hits, tracks) and reconstruction level needs to be adapted to the changes. In particular, Fermilab expertise in Geant4, tracking, and calorimetry fits ideally to the needs that include the implementation and validation of detector geometry and material, development of software to access new reconstruction information, implementation of trigger algorithms, particle flow clustering using the new detector segmentation, commissioning of analysis-level reconstruction quantities (tracks, PF particles, physics objects), and performing physics analyses well targeted to the physics interests and detector capabilities in the SLHC era to demonstrate the gains achieved with the upgraded detector.

The Fermilab CMS group has the opportunity to lead and be a principal player in many areas related to the CMS offline upgrade program. The skills and expertise of the staff in the SCD-CMS and SCD-ADSS departments are a key asset for Fermilab to contribute to software core activities such as framework and toolkit re-engineering to adapt the CMS software to future computing technologies. The interaction among these groups and Fermilab and university physicists and engineers working at the LHC Physics Center (LPC) on detector improvements, physics object reconstruction, and physics analysis to make the case for the upgraded detectors, is unique and should be exploited.

Upgrade Task	Shutdown	Motivation

Table 5: *Summary of Software Framework and Offline Reconstruction activities.*

3.9 Computing, Data Handling and Operations

Within CMS computing, Fermilab is a leader in providing workload management and data management capabilities to the experiments, and is coordinating the computing operations efforts within CMS. Fermilab provides the core team and leadership to the CMS computing efforts. Fermilab scientists leading the CMS Computing efforts since 2006, with Bauerdick, McBride and Fisk serving terms as CMS computing coordinators, and Bauerdick and Fisk being Software and Computing Manager and deputy for the U.S. CMS program. Members of the Fermilab group serve as Level-2 managers within the CMS computing efforts, including Evans and Vaandering as Workload Management and Data Management coordinators, Bauerdick and Gutsche as Data Operations and Computing Operations Coordinator, Mason and Hufnagel as

Computing Integration Coordinators.

Computing and data handling faces significant challenges when the luminosity increases. Data sets are growing with the complexity and size of events increasing at higher specific luminosity and pile-up. Beyond that, CMS is discussing to increase the HLT output rate very significantly above the current 300Hz, and future rates of up to 10 kHz of event rate into the offline systems are being discussed. This poses huge challenges to data handling, storage capacities and data access.

With the planned computing upgrades not only the capacity is increasing but also the different systems and networks are getting much more complex. The number of cores per worker-node unit is ramping up, given that increases in computing capacity can only be achieved by adding compute cores while the performance per core stays constant. This requires not only changes to the software frameworks to allow parallel processing as described above, but also significant upgrades to the job scheduling and the data access systems, posing new challenging distributed computing problems.

The current 2011/2012 run has shown the limits of the current computing systems. While the overall performance was sufficient the requirement of very short turn-around times to get the physics results out quickly uncovered important shortfalls and the need to re-engineer parts of the distributed computing and data handling environment. Such an effort has already started for the distributed physics analysis job submission system. Computing is planning to address the operational latencies and turn-around time limitations of the current system, which will likely need significant extensions and changes to the computing environment. This re-engineering will also address the need for a large improvement in overall throughput of the computing production system, given the increases in data sizes and event samples.

Fermilab has excellent expertise in distributed computing, in workflow systems, in data access, computer security and distributed computing technologies, and has close working relationships with the computer science leaders in this field. For example, Holzman was leading the glideIn-WMS project, together with computer scientists at USC/ISI, and the Tier-1 group has expert staff to work on these problems. The Accelerator and Detector Simulation Support (ADSS) department has established track record in workflow systems. The engineering strength of the Scientific Computing Division at Fermilab will allow the Fermilab group to take major responsibilities in the computing upgrades and to prepare for data taking in 2014 and beyond.

These computing systems engineering and operations efforts go hand-in-hand with the planned upgrades of the computing facilities and the networking capabilities that the Fermilab group is planning for the Tier-1 and LPC Analysis facilities. They also are synergistic to the planned upgrade work on the CMS software framework described above.

Upgrade Task	Shutdown	Motivation

Table 6: *Summary of Computing, Data Handling, and Operations upgrade activities.*

3.10 Data Quality Monitoring

Data quality monitoring is essential to collecting physics quality data. Events are distributed in real time to dedicated monitors that generate detector specific reference histograms. Problems are detected by the shift crew when monitoring historgrams deviate from reference histograms. The goal is to detect problems as soon as possible and take corrective action to avoid significant loss of data. Online DQM is the primary tool used by CMS to monitor the data collection in real time. The Data Quality Monitoring (DQM) and the Web-Based Monitoring (WBM) services developed at Fermilab for CMS have proved to be essential for effective data taking and for achieving physics results.

Each detector group is responsible for certifying data, and the certification results are used to create the certified datasets for physics analyses. The DQM team developed the framework for the online DQM, offline data certification, and also developed the Web Based Monitoring interface to facilitate access to the information used for monitoring. Having easy access to the monitoring data allows experts located remotely and at all hours to provide critical feedback. The tools help categorize problems and identify the leading sources of lost data so that effort can be applied to the maximize the collection of good data.

DQM will require continuous updates and maintenance during LS1 so that CMS can retain the same functionality before and after LS1. For example, the way the data from the detector will be delivered is expected change and the DQM interface will have to be updated. Maeshima is co-chairing a task force to plan monitoring upgrades during LS1. The upgraded services are needed for running in 2014 and beyond.

Upgrade Task	Shutdown	Motivation

Table 7: S*ummary of Data Quality Monitoring upgrade activities.*

4. Fermilab Strengths and Unique Capabilities

Fermilab has experienced staff, unique capabilities, and facilities that should be leveraged for work on CMS upgrades. For example, Fermilab has experienced ASIC engineers and electronics engineers who have domain knowledgeable relevant to the upgrades. There are experts at the laboratory involved as convenors of the DPG, POGs, PAGs, and upper levels of CMS management who understand CMS upgrade needs. Fermilab has computing facilities that make data access easy and the Remote Operations Center, which provides a facility for DQM shifts. As the host laboratory for USCMS and as host for the LHC Physics Center (LPC), Fermilab is in a unique position to apply the strengths and capabilities available at the laboratory to establish a leadership role and contribute to CMS upgrades. This section summarizes Fermilab strengths and unique capabilities.

4.1 Detector Fabrication Assembly Facilities

Silicon Detector Facility (SiDet)

The SiDet facility supports production assembly and wirebonding of silicon strip and pixel detectors and specializes both in assembly of detector subassemblies and complete detectors.

The SiDet facility has the following features:

- 5,000 sq. ft. Class 10,000 clean room, and 200 sq. ft. Class 100 inner clean room.
- Full wirebonding capabilities and a large number of Coordinate Measuring Machines (CMMs) for precision metrology of ladders and subassemblies.
- Testing facilities, including a new probe station with chuck capable of 200mm wafers and temperature control from -55C to 200C, and several thousand square feet of additional teststand space.
- CO_2 cooling teststand (USCMS funded) for testing detectors under real operating conditions.

Both the CMS FPIX detector and the CMS Tracker Outer Barrel detectors were assembled at SiDet. Possible future CMS projects for SiDet are: testing of prototype sensors, FPiX assembly, and barrel strip detector assembly.

CNC plastics facility (Lab 8)

Lab 8 at Fermilab is a Computer Numeric Control (CNC) facility for accurately cutting, drilling and milling plastics. The facility is used for machining scintillator and G10, for example, and can machine pieces up to 5 ft. x 18 ft. During the CMS construction project, all the panels for the CMS endcap CSC detectors were machined at Lab 8, including cutting, drilling and strip milling the 5 ft. x 12 ft. panels. Currently, additional panels are being produced to populate the final two stations in the muon endcaps (ME4/2), which will be installed during LS1.

Sctintillation Detector Facility (Labs 6 and 7)

Fermilab houses a facility for extruding scintillator with both a small scale prototype capability and a medium scale production capability (used for MINERvA, for example). It is also a chemistry lab for analysis of materials.

Thin Film Deposition Facility (Lab 5)

This facility specializes in cutting, polishing and mirroring optical fibers, such as scintillating or wavekength-shifting fibers. It is capable of making thin film depositions on many different substrates, and was used to prepare fibers for the CMS HCAL.

Lab 3

Lab 3 houses a facility for layup of custom carbon fiber structures. It contains about 3000 sq. ft. of Class 10,000 clean room with 120 sq. ft. of portable inner clean room down to below Class 100. The facility also houses a large CMM.

4.2 Fermilab Test Beam Facility (FTBF)

FTBF consists of two versatile beamlines (MTest and MCenter) in which users can test equipment or detectors. The MTest primary beamline consists of a beam of high energy protons (120 GeV) at moderate intensities (approx. 1-300 kHz). This beam can be targeted to create secondary, or even tertiary particle beams of energies below 1 GeV, consisting of pions, muons, and electrons. The MCenter beamline is similar to the MTest beamline. The goal of the FTBF is to provide flexible, equal and open access to test beams for all detector tests, with a guarantee of safety, coordination and oversight.

4.3 Engineering Expertise in PPD

ASIC Engineering

Fermilab has a strong engineering group with seven engineers that have expertise in analog, digital, and mixed signal design. In the past, the group has made designs with feature size down to 130nm and 3D technology, and the group is now exploring 65nm technology.

- Testing of prototypes on probe station and with custom personality cards.
- Automated production testing of packaged IC's on custom testing robot.
- Designed CMS HCAL QIE readout chip.

Electronics Design Engineering

- Design PCBs, FPGA design, system architecture, cabling, power, and project engineering.
- Designed CMS HCAL frontend electronics and provided HCAL project electrical engineering.

Mechanical Design Engineering

- Full range of mechanical design capabilities including large scale steel, large scale plastic structures (for example, NOvA detector) and design of low mass detector structures.
- Design of cooling and cryogenic systems (for example, CO_2 cooling teststand)
- Finite Element Analysis including fluid flows and magnetic fields
- Design work for CMS FPIX

4.4 Electronic System Engineering Department in SCD

It has an experienced team of engineers, technicians, and physicists. Currently, involved in the CMS upgrade include the Pixel Optohyrid for the whole pixel upgrade, investigating VTRX/VTTX and GLIB for the HCAL upgrade. The department has acquired over the last three years a lot of equipment and tools and is now amongst the best equipped optical laboratory in the HEP community. The department is also responsible for supporting testing of rad-hard sensors and DC-DC conversion for the pixel upgrade.

4.5 Software Engineering and Physics Tools in SCD

Fermilab has significant expertise in software engineering and physics tools in the SCD-CMS and SCD-ADSS departments.

- Past and Current contributions: designed the CMS software framework, lead offline, simulation, physics tools efforts. Developed, validated, and supported the event generator (Pythia), detector simulation (Geant4), ROOT software tools.
- Future: in partnership with CERN, lead the software transition toward the high performance computing era.

4.6 The LHC Physics Center (LPC)

Fermilab hosts the LHC Physics Center. The LPC provides a center that attracts postdocs and students. The LPC performs many tasks, including:

- Organizing seminars. Seminars organized by the LPC cover physics measurements by all LHC experiments, as well as talks by theorists on the physics potential of the LHC.
- Organizing schools. The LPC organizes regular data analysis schools for CMS members, to school those members new to data analysis or CMS software in topics covering analysis strategies and CMS specific algorithms and tools. These schools have been very successful, and the LPC has consulted with non-USCMS groups in setting up their own data analysis schools.
- LPC fellows program. The LPC fellows programs is a competitive program to encourage both young and senior researchers to contribute to the LPC by offering modest support during their residence at Fermilab and an independent travel budget for attending conferences and giving seminars.

The LPC is a central location for USCMS that provides a lower cost alternative to sending people to CERN. In some cases universities send their students to the LPC for extended periods of time, and ask that they be supervised by someone resident at the LPC.

4.7 Computing Resources

Fermilab hosts the largest CMS Tier 1 center and has substantial computing resources available for analysis, monitoring, and commissioning activities. A large LPC CAF and Tier 3 makes Fermilab an attractive computing center. Many people from CERN utilize Fermilab computing for analysis as well as commissioning and operations activities.

4.8 Remote Operations Center (ROC)

The ROC has been used by USCMS members to take offline DQM shifts and by detector groups for monitoring shifts. These shifts count towards the service credit for authorship. The ROC has direct communication links to the CMS Control Room at Point 5 and has easy access to computing resources at Fermilab. The HCAL prompt feedback group has used the ROC for informal shift to look at data in near real time. The ROC provides a cost effective alternative to sending people to CERN for shifts, and we can expect that this resource will become increasingly attractive. The ROC is used when commissioning data are collected, and will be used to verify the functionality of upgrades during LS1.

Not all USCMS groups have taken advantage of the ROC and there should be an evaluation of the expected usage during LS1. It would be useful to review the use cases and determine what improvements can be done in order to have universities take greater advantage of this resource.

5. Goals and Recommendations

This section addresses the six goals for Fermilab participation in CMS upgrades, which were mentioned in the "Strategic Vision and Goals" section of this document. For each goal there are recommendations on how to proceed.

Goal #1: Identify opportunities for work on CMS upgrades that are well matched to laboratory expertise and available resources, and establish Fermilab commitments within CMS.

The following opportunities for work on CMS upgrades that are well matched to laboratory expertise have been identified:

1. Track trigger R&D
2. L1 trigger
3. High Precision Spectrometer
4. Forward Detector Upgrade for HL-LHC
5. Global Event Description (GED)

The next step is to determine if there are available resources at Fermilab so that the CMS group can commit to taking on new responsibilities.

Goal #2: Identify core upgrade activities and continuing responsibilities, and ensure that these activities and responsibilities have the necessary resources to be successful.

The core upgrade activities and continuing responsibilities are those activities to which Fermilab is committed. These activities should be supported to ensure that they succeed. They include the following:

1. Forward pixels (FPIX)
2. Hadron calorimeter (HCAL)
3. Framework and offline software
4. Upgrade simulation and physics case
5. Computing Infrastructure
6. Data Handling and Operations
7. Remote Operations Center (ROC)
8. Data Quality Monitoring (DQM)
9. Central data acquisition system (DAQ)
10. Muon Detector Panel Fabrication

Goal #3: Work towards establishing leadership positions in CMS upgrade activities for Fermilab staff.

The LHC has proven to be capable of quickly increasing the luminosity and the Fermilab CMS group needs to be able to adapt and participate in new detector upgrade opportunities provided that they do not pose a risk to the core tasks and there are available resources to be successful.

The Fermilab CMS group will have to compete for resources at the laboratory. Although the energy frontier program has high priority, it is important o ensure that the CMS effort remains an integral part of the laboratory's future. It is also important to have an understanding of what fraction of resources are available for the CMS effort. Ideally there should be some flexibility to react to problems and new physics directions that may require rebalancing priorities.

Goal #4: Develop partnerships with CMS collaborating institutions and the LPC in order to establish Fermilab as an important center for CMS upgrade activities.

The Fermilab CMS group should aggressively pursue strategic partnerships with the LPC, universities, and Fermilab's Particle Physics Division that are mutually beneficial and support core activities. In particular the group should work on developing the LPC into an important center for CMS upgrades that remains active through the different stages of CMS.

Upgraded detectors will have new capabilities and provide additional information making it necessary to update reconstruction code to take advantage of the enhanced capabilities. It is essential to justify the physics case for the upgrades using an accurate simulation. Optimized reconstruction in the presence of very high pileup is needed in order to justify the upgrade choices. Current reconstruction software is not appropriate for the upgrade studies and development of the Global Event Description (GED) at all levels from algorithm development, integration of new detector inputs, to calibration is needed. This is a high profile and critical area in CMS where additional input is needed, and the LPC can play a leading role in this effort. The LPC fellowship program can help bring outside expertise on the GED to help focus the activities.

Other areas of strong local expertise includes upgrades for the HCAL, tracker, track trigger and forward detectors. These areas all provide opportunities for CMS fellows to take on leading roles and to work together with the local experts. Another area where important contributions can be made is with the trigger for the higher luminosity conditions.

In some cases universities send students and postdocs to the LPC and ask for help with their supervision. We should be actively looking for available people to help support our core tasks.

Goal #5: Identify upgrade projects that are beneficial to maintaining or improving capabilities at Fermilab.

Fermilab engineering resources and facilities should be part of all stages of CMS upgrades to ensure the long term vitality of the laboratory and to avoid loss of talented people. The following capabilities should be maintained, improved, and in some cases new capabilities should be established. CMS upgrade projects can provide the necessary impetus.

- SiDet is a facility that has had considerable investment, plays a key role in silicon upgrades, and employs many engineers and technicians.

- Fermilab’s ASIC engineering group is a world class ASIC development team that has expertise in analog, digital, and mixed signal design, and there is no question that this group can make important contributions to the upgrades.
- MicroTCA s an industry standard and a technology that is being deployed in CMS during LS1 and beyond. Fermilab has very little expertise in this area and should begin developing it in order to stay current.
- Specialized expertise at Fermilab should be maintained. For example, building CSC muon chambers, where Fermilab machined the CSC muon chambers for the construction project (2870 panels all together) and assembled 150 muon chambers (about 37% of the total number of chambers). The chambers were shipped to “fast sites” at U. Fl. and UCLA for final integration and testing before shipping to CERN. Fermilab would have been a natural site to build the final round of chambers, however the cost of labor and overhead at the lab was too high to be competitive and as a result, a new chamber assembly factory was built at CERN with help from Fermilab staff. The vitality and reputation of the laboratory depends on maintaining and improving expertise in detector R&D, as well as building and testing detectors. In this case a modest commitment by the laboratory to keep chamber production at Fermilab would have been a good investment.
- Fermilab has a team of software engineers, computer scientists, and physicists in its Scientific Computing Division who are principal developers of the CMS software frameworks and physics tools such as the Pythia event generator and the Geant4 detector simulation tool kit. This team has partnered with the CERN software group to investigate alternatives to parallelize HEP software frameworks and adapt to the coming computer hardware technology used in high performance computing. This R&D effort will evolve into prototypes and eventually a parallel framework and physics tools to be deployed in the timescale of LS2. An adequate level of support to this effort will allow Fermilab to remain a strong player in the areas of software frameworks and physics software tools for HEP applications as CMS and the world enters the era of high performance computing.

Goal #6: Ensure that postdocs are engaged in upgrade activities and that they are aligned with Fermilab objectives.

A comprehensive plan for Fermilab postdocs should be agreed on between mentors and their postdocs to ensure they develop a competitive set of skills enabling them to standout when competing for jobs. When appropriate, Fermilab postdocs should be engaged in upgrade activities in order to gain hardware/detector experience that will help them in their search for their next position.